The Fourth Generation t-prime in Extensions of the Standard Model

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We study the effects of a fourth generation t' quark in various extensions of the standard model. In the Randall-Sundrum model, the decay $t' \to tZ$ has a large branching ratio that could be detected at the Large Hadron Collider (LHC). We also look at the two-Higgs doublet models I, II and III, and note that, in the latter, the branching ratio of $t' \to t\phi$, where ϕ is a Higgs scalar or pseudoscalar, is huge and we discuss detection at the LHC. A few comments about the minimal supersymmetric standard model are also included.

I. INTRODUCTION

Interest in a sequential fourth generation has waxed and waned over the years [1, 2]. Shortly after the discovery of the third generation, a fourth generation was an obvious extension. However, interest in a fourth generation dropped substantially after measurement of the number of light neutrinos at the Z pole showed that only three light neutrinos could exist. The discovery of neutrino oscillations suggested the possibility of a mass scale beyond the standard model, and models with a fourth generation containing a sufficiently massive neutrino became acceptable. In the early part of this decade, it was thought [3] that electroweak precision measurements ruled out a fourth generation, however it was subsequently pointed out [4] that if the fourth generation masses are not degenerate, then these constraints can be evaded. More recently, Kribs et al. [5] showed that a mass splitting of $40-60$ GeV between the fourth generation quarks results in S and T parameters which are within the one-sigma error ellipse.

Most analyses of the phenomenology of a sequential fourth generation have focused on the minimal Standard Model. In this paper, we consider the phenomenology of the fourth generation t' in popular extensions of the Standard Model. In Section II, we discuss the Randall-Sundrum model and show that one expects a relatively large branching ratio for the flavor-changing decay $t' \to tZ$, which could be detected at the LHC. In Section III, we study the two-Higgs doublet models (Models I, II and III), and show that in Model III, the decay $t' \to t\phi$, where ϕ is either a Higgs scalar or pseudoscalar, can have a huge branching ratio (as high as 95%) and we discuss the rather dramatic phenomenology at the LHC. Finally, in Section IV, we present our conclusions.

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II. RANDALL-SUNDRUM MODEL

The Randall-Sundrum model (RS1) [6] is a popular solution to the hierarchy problem, where the warped geometry of an additional dimension is responsible for generating TeV scale physics from a more fundamental Planck scale. In the original RS1 model, the standard model (SM) fields were confined to the TeV brane, but it was quickly noted that they could be placed in the bulk without problems [7, 8, 9]. This led to a natural resolution of the flavor hierarchy problem.

In the basis of diagonal bulk masses, the normalized wavefunction of zero-mode fermions is given by [7, 8, 9]

$$f^{(0)}(c_f, z) = \left[\frac{k(1 - 2c_f)(kz)^{(1-2c_f)}}{e^{\beta(1-2c_f)} - 1} \right]^{1/2}, \quad (1)$$

where $\beta = kR\pi \approx 37$, $1/k \leq z \leq e^\beta/k$ and c_f is the 5-D mass parameter describing the location of the fermion in the bulk. For $c_f < 1/2$ ($c_f > 1/2$) the fermion ψ_f lives near the TeV (Planck) brane since its resulting Yukawa coupling with the Higgs field becomes large (small). Since the Kaluza-Klein (KK) modes lie near the TeV brane, the heavier fermions have larger couplings to KK bosons. As noted by Agashe et al. [10, 11], there is mixing between the Z-boson and the KK-Z boson, resulting in a shift of the fermionic couplings to the Z.

In this model, the portion of the Lagrangian responsible for SM flavor violation is given by [11]

$$\mathcal{L}^Z \sim g_z \beta \Delta Z^\mu \sum_f \overline{\psi}_f^{(0)} \gamma_\mu \frac{1}{f_f^2} (v_f - a_f \gamma_5) \psi_f^{(0)}, \quad (2)$$

where $g_z = \frac{g_2}{2\cos\theta_W}$ and $\Delta = \left(\frac{M_Z}{M_{KK}}\right)^2$. The vector and axial vector coefficients depend on the fermion ψ_f and are given by $v_f = T_3^f - Q_3^f \sin^2\theta_W$, and $a_f = T_3^f$. The constants f_f are given in terms of equation 1 by $\sqrt{2k}/f_f = f^{(0)}(c_f, e^\beta/k)$. Lastly, $\psi_f^{(0)}$ is the zero-mode of the 4-D fermion field in the basis of diagonal 5-D bulk masses. However, this basis is not the same as the basis in which the 4-D mass terms are diagonal. This gives

rise to flavor violating terms in the 4-D basis, which have larger couplings for heavier fermions.

Using this formalism, Agashe et al. [10] point out that with three generations, the branching ratio for $t \to cZ$ is of $\mathcal{O}(10^{-5})$ for a KK-Z mass of 3 TeV. This is a significant increase from the SM value. In the case of a fourth generation however, there are no electroweak precision constraints and so very large flavor changing neutral currents (FCNC) are allowed. In particular, one expects to observe $t' \to tZ$ at a large rate. Due to the fact that the t' and the b' have nearly degenerate masses, the decay of the t' is dominated by $t' \to Wb$ unless the mixing angle is very small. Thus the decay rate for $t' \to Wb$ is proportional to $|V_{t'b}|^2 \sim |(U_f)_{34}|^2$, where (U_f) is the mixing matrix that arises when expanding out the 4-D fermion fields from equation 2 in the basis of diagonal 4-D mass terms. Thus the $|V_{t'b}|^2$ factor in $\Gamma(t' \to Wb)$ conveniently cancels the $|(U_f)_{34}|^2$ factor in $\Gamma(t' \to tZ)$ when calculating the branching ratio BR$(t' \to tZ)$.

The decay rate and branching ratio for $t' \to tZ$ depend on the four 5-D mass parameters for the left and right handed t and t'. Two of these can be eliminated in favor of the t and t' masses. Using the central value of c_{t_L} given by Agashe [11], the number of free parameters is reduced to the t' mass and the fermion mass parameter $c_{t'_L}$, which describes the location of the t' in the bulk.

The results for the branching ratio are given in Figure 1 for t' masses of 400 and 500 GeV. As one varies the third generation mass parameter c_{t_L} parameter (discussed in the previous paragraph) over a reasonable range, this result changes by less than a factor of two. We find a branching ratio of $\mathcal{O}(10^{-3} - 10^{-2})$.

ATLAS [12] has claimed that a bound of 10^{-5} can be reached in $100\,\mathrm{fb}^{-1}$ for $t \to cZ$. Since the Z energy in the $t' \to tZ$ decay is similar to that in $t \to cZ$, one can get a rough estimate of the sensitivity by simply scaling this by the production cross section. This gives a sensitivity of 10^{-3} for $t' \to tZ$. One can probably do substantially better if one includes the fact that the t in the decay can be detected, which will help eliminate backgrounds. It is clear that this places the decay within reach of the LHC, although a more precise analysis would be welcome.

How does this branching ratio compare with other models? The most comprehensive study concerning FCNC in the four generation Standard Model is the work of Arhrib and Hou [13]. They considered loop induced FCNC decays of fourth generation quarks, plus effects of fourth generation quarks on FCNC decays of third generation quarks. They found that the decay $t' \to tZ$ can occur in the standard model with a branching ratio of $\mathcal{O}(10^{-5} - 10^{-4})$ and suggest that this may be measurable at the LHC. In the Randall-Sundrum case, the branching ratio will be larger by approximately a factor of 100. What about flavor models? We know of no such models for four generations. One of us (MS) is studying such a model, but the rate will be similar to that of Arhrib and Hou (additionally, flavor models do not typically give large rates for $t \to cZ$). It is also likely that
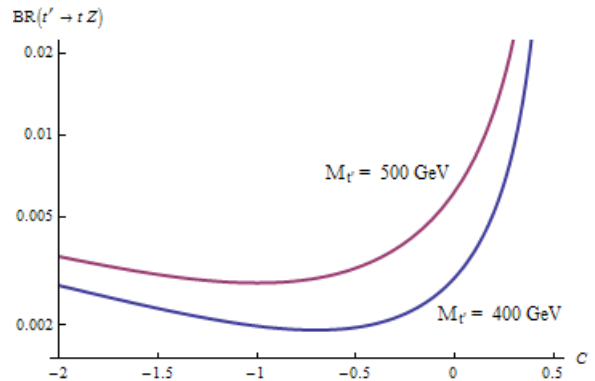

FIG. 1: Branching Ratio for $t' \to tZ$ as a function of the fermion mass parameter $c_{t'_L}$.

other models will have a rate for $t' \to t\gamma$ or $t' \to tg$ which is comparable to $t' \to tZ$, unlike the Randall-Sundrum case.

III. TWO HIGGS DOUBLET MODELS

Among the most popular extensions of the Standard Model are two Higgs doublet models [14]. The most common is called Model II. In the two Higgs doublet model II, due to a discrete symmetry, the down-type quarks and leptons couple to one complex doublet ϕ_1 while the up-type quarks and neutrinos couple to the other ϕ_2. The ratio of vacuum expectation values (vev) is a free parameter defined by $\tan(\beta) = v_2/v_1$. By requiring that the theory be perturbative we obtain a bound on the possible values of $\tan(\beta)$. The Yukawa couplings of fourth generation quarks are given by $g_{t'}/\sqrt{2} = m_{t'}/v_2$ and $g_{b'}/\sqrt{2} = m_{b'}/v_1$, where $v^2 = v_1^2 + v_2^2 = (246\mathrm{GeV})^2$. If we approximate $m_{t'} \sim m_{b'} \equiv M \gtrsim 280$ GeV and relate v_1 and v_2 to the Standard Model Higgs vev v in terms of $\tan(\beta)$, then the theory will remain perturbative, $g_{t'}^2 < 4\pi$ and $g_{b'}^2 < 4\pi$, only if

$$\frac{1}{\sqrt{2\pi(v/M)^2 - 1}} < \tan(\beta) < \sqrt{2\pi(v/M)^2 - 1} \,. \quad (3)$$

Thus for Model II with $M \geq 280$ GeV we find $1/2 < \tan(\beta) < 2$. In Model I the ϕ_1 field does not couple to fermions, which eliminates the upper bound, the lower bound however remains unchanged.

Issues of perturbation theory and vacuum stability pose a challenge to four-generation models. As noted most recently by Kribs [5], in the Standard Model the large Yukawa couplings will cause the scalar self-coupling to either go negative (leading to vacuum instability) or reach a Landau pole well before the GUT scale. The Yukawa coupling itself can also reach a Landau pole at relatively low scales. Although methods can be found to extend the reach of perturbation theory [15], they do involve addition of new physics just above the TeV scale. In
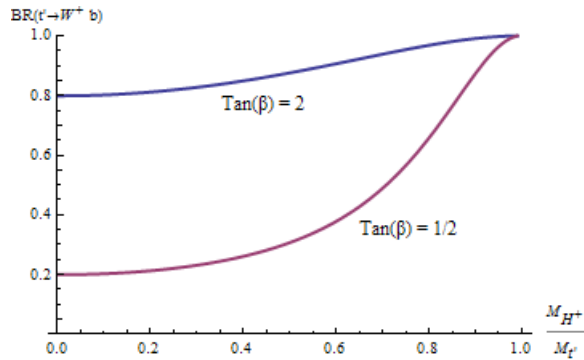
FIG. 2: Branching Ratio for $t' \rightarrow Wb$ as a function of the ratio $M_{H^+}/M_{t'}$.

the two Higgs doublet models, the situation is much more complicated since there are many scalar self-couplings, many other vacua (such as charge-breaking vacua) and many other opportunities for instabilities. Our approach here is to assume that the two Higgs doublet model is an effective theory below the TeV scale, and will presume that physics above that scale will not substantially affect our results.

Since the charged Higgs $H^{\pm}$ is a possible decay product of the t' through the decay $t' \rightarrow Hb$, and this decay will be very difficult to observe, there will be a slight suppression in the branching ratio BR($t' \rightarrow Wb$), which is shown in Figure 2 as a function of the charged Higgs mass.

A much more interesting situation arises in Model III. In Model III, there is no discrete symmetry prohibiting tree level flavor changing neutral currents. Initially this appears to be very problematic. However if one goes to a basis in which one of the scalar fields gets a vacuum expectation value and the other does not, then the couplings of the latter, ϕ, will be, in general, flavor changing. By analyzing various mass matrix textures, Cheng and Sher [16] argued that fine-tuning can be avoided if the flavor changing neutral couplings $\xi_{ij}\overline{f}_i f_j \phi$ are given by

$$\xi_{ij} = \lambda_{ij} \frac{\sqrt{m_i m_j}}{v/\sqrt{2}} \qquad (4)$$

and the couplings λ_{ij} are of $\mathcal{O}(1)$. In other words, the flavor changing Yukawa couplings are the geometric mean of the two Yukawa couplings of the fermions involved. Model III is defined as the two Higgs doublet model with Yukawa couplings given by the above expression. Recent studies [17] of heavy quark mixing and decays have begun exploring interesting regions of parameters space (which depends on the λ_{ij} and the relevant Higgs masses). Note that in this model, the flavor changing couplings of the light quarks are very small, and the constraints from kaon physics are not as severe. Only a few studies of Model III have been done [18, 19, 20] involving fourth generation fields.

In this Model, one would expect an enormous flavor

changing coupling between the t', the t and the ϕ. The coupling, in fact, would be substantially larger than the top quark Yukawa coupling. If kinematically accessible, then one would expect $t' \rightarrow t\phi$ to overwhelmingly dominant t' decays. Here, ϕ can be the combination of neutral scalars that is orthogonal to the state that gets a vev, or it can be the pseudoscalar. In either event, this decay will dominate.

The cross section for producing a 400 GeV t' is 15 picobarns [21]. Virtually all of these t's will decay into $t\phi$, leading to a dramatic $t\bar{t}\phi\phi$ signature. If ϕ is a pseudoscalar or a neutral scalar lighter than about 140 GeV, then it will decay into $b\bar{b}$, leading to a $6b, 2W$ final state. The biggest Standard Model background to these events would come from double pair production of $t\bar{t}b\bar{b}$. The cross section for this background [22] is approximately 2 picobarns, and it gives a $4b, 2W$ final state. If one only looks at events with three or more tagged b's and one or more leptons, and assumes a b-tag efficiency of 40%, then the signal will pass the cut 20% of the time, and the background will pass the cut 8% of the time, leading to a signal of 3150 fb and a background of only 160 fb. Thus, it appears that the signal will easily be detectable, possibly in an early run at the LHC.

If ϕ is a neutral scalar heavier than 140 GeV, then it will decay into WW leading to a $2b, 6W$ final state. Here, if one looks at events with three or more leptons and one or more tagged b's, then 12% of the decays will pass the cuts, leading to an event rate of 1.8 picobarns. We know of no standard model background that comes close to this signal. This signal would also be easily detectable at the LHC.

IV. CONCLUSIONS

There continues to be interest in the phenomenology of a sequential fourth generation. Yet almost all discussion have been in the context of the Standard Model. In this paper, we have explored the phenomenology of the fourth generation, focusing on the t' quark, in extensions of the Standard Model. In the Randall-Sundrum model, the decay $t' \rightarrow tZ$ can occur at a rate approaching one percent, which should be detectable at the LHC. In two-Higgs doublet model, one gets a suppression of the branching ratio $t' \rightarrow Wb$ in Models I and II, but in Model III the decay of $t' \rightarrow t\phi$, where ϕ is a scalar or pseudoscalar, dominates the decay, leading to spectacular $t\bar{t}\phi\phi$ signatures at very large rates, which could be detected during the early months of running at the LHC.

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